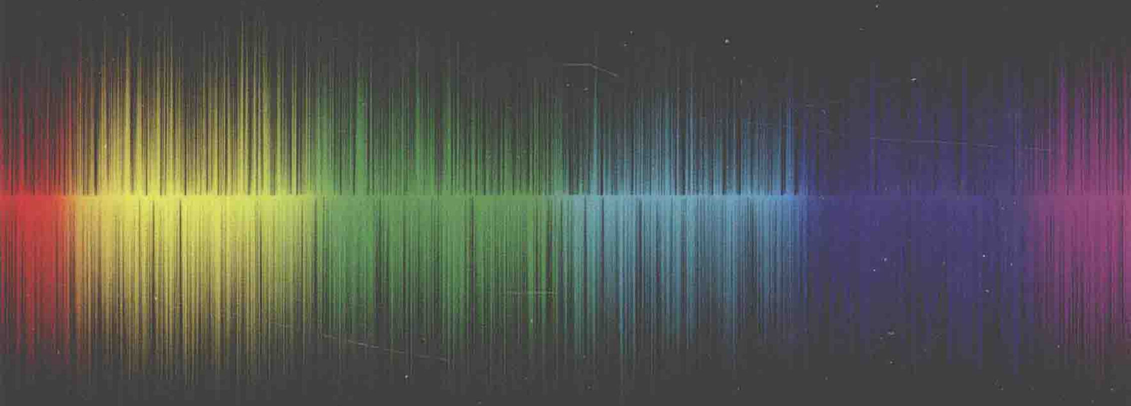

ANALOG AND MIXED-SIGNAL ELECTRONICS

KARL STEPHAN

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PREFACE

All but the simplest electronic devices now feature embedded processors, and software development represents the bulk of what many electrical engineers do. So, some would question the need for a new book on analog and mixed-signal electronics. Surely everything about analog electronics has been known for decades and can be found in old textbooks, so what need is there for a new one?

In teaching a course on analog and mixed-signal design for the past few years, I have found that as digital and software design has taken over a larger part of the electrical engineering curriculum, some important matters relating to analog electronics have fallen into the cracks, so to speak. Problems as simple as wiring up a dual-output power supply for an operational amplifier circuit prove daunting to some students whose main engineering tool up to that point has been a computer. While all undergraduate electrical engineering students master the basics of linear circuits and systems, these subjects are often taught in an abstract, isolated fashion that gives no clue as to how the concepts taught can be used to make something worth building and selling, which is what engineering is all about.

This book is intended to be a practical guide to analog and mixed-signal electronics, with an emphasis on design problems and applications. Many examples are included of actual circuit designs developed to meet specific requirements, and several of these have been lab-tested, with experimental results included in the text. While advances in analog electronics have not occurred as rapidly as they have in digital systems and software, analog systems have found new uses in concert with digital systems, leading to the prominence of mixed-signal systems in many technologies today. The modern electrical engineer should be able to address a given design problem with the optimum mix of digital, analog, and software approaches to get the job done efficiently, economically, and reliably. While most of a system's functionality may depend on software, none of it can get off the ground without power, and power supplies are largely still an analog domain.

Beginning with reviews of electronic components and linear systems theory, this book covers topics such as noise, op amps, analog filters, oscillators, conversion between analog and digital domains, power electronics, and high-frequency design. It closes with a chapter on a subject that is rarely addressed in the undergraduate curriculum: electromagnetic compatibility. Problems having to do with electromagnetic compatibility and electromagnetic interference happen all the time, however, and can be very difficult to diagnose and fix, which is why methods to detect and diagnose such problems are included. Although familiarity with standard electrical engineering concepts such as complex numbers and Laplace transforms is assumed in parts of the text, other parts can be used by those without a calculus or electrical engineering background: technicians, hobbyists, and others interested in analog and mixed-signal electronics, but who are not members of the electrical engineering profession. References for further study and a set of problems are provided at the end of each chapter, as well as an appendix describing test equipment useful for analog and mixed-signal work.

San Marcos, TX
July 3, 2014

KARL D. STEPHAN

ACKNOWLEDGMENTS

"No man is an island, Entire of itself," as John Donne's poem says, and this book is my work only in the sense that I am the medium through which it passes. Many educators, mentors, and friends contributed to the knowledge it represents. Among these, I should mention first the late R. David Middlebrook (1929–2010), whose electronics course I took as a Caltech undergraduate in the 1970s. Professor Middlebrook never met an analog circuit he couldn't analyze with nothing more than paper, pencil, and a slide rule, and his disciplined and insightful approach to analog circuit analysis is an ideal that I am sure I fall short of. I can only hope that some of the clarity and depth with which he taught shows through in this text. In my 16 years at the University of Massachusetts Amherst, I shared teaching responsibilities with my colleagues and friends Robert W. Jackson and K. Sigfrid Yngvesson. Bob Jackson in particular was never the one to let a mathematical or technical ambiguity slip by, and I thank him for the quality check he performed on any lecture material we presented jointly. A. David Wunsch, for many years a professor at the University of Massachusetts Lowell, reviewed a draft of Chapter 7 and made helpful suggestions for which I am grateful. The course entitled "Analog and Mixed-Signal Design" was developed at my present institution, Texas State University, to form part of a new Electrical Engineering program initiated in 2008. The founding Director of the School of Engineering, Harold Stern, was kind enough to give me a free hand in developing a lab-based course which has an unconventional structure, consisting of four or five multi-week projects interspersed with lectures. I thank him for creating a congenial teaching environment that helped me to develop the material that forms the basis of this text. I also thank historian of science Renate Tobies for providing information on Heinrich Barkhausen that is not generally available in English.

Finally, I express my appreciation and gratitude to my wife Pamela, whose artistic skills provided the templates for most of the illustrations. Together we can say, "Be thankful unto him, and bless his name. For the Lord is good; his mercy is everlasting, and his truth endureth to all generations."

ABOUT THE COMPANION WEBSITE

This book is accompanied by a companion website:

http://wiley.com/go/analogmixedsignalelectronics

The website includes:

- Solutions Manual available to Instructors.

CONTENTS

1

INTRODUCTION TO ANALOG AND MIXED-SIGNAL ELECTRONICS

1.1 INTRODUCTION

"In the beginning, there were only analog electronics and vacuum tubes and huge, heavy, hot equipment that did hardly anything. Then came the digital—enabled by integrated circuits and the rapid progress in computers and software—and electronics became smaller, lighter, cheaper, faster, and just better all around, all because it was digital." That's the gist of a sort of urban legend that has grown up about the nature of analog electronics and **mixed-signal** electronics, which means simply electronics that has both analog and digital circuitry in it.

Like most legends, this one has some truth to it. Most electronic systems, ever since the time that there was anything around to apply the word "electronics" to, were analog in nature for most of the twentieth century. In electronics, an **analog signal** is a voltage or current whose value is proportional to (an analog of) some physical quantity such as sound pressure, light intensity, or even an abstract numerical value in an **analog computer**. **Digital signals**, by contrast, ideally take on only one of two values or ranges of values and by doing so represent the discrete binary ones and zeros that form the language of digital computers. To give you an idea of how things used to be done with purely analog systems, Figure 1.1 shows on the left a two-channel vacuum-tube audio amplifier that can produce about 70 W per channel.

The vacuum-tube amplifier measures 30 cm × 43 cm × 20 cm and weighs 17.2 kg (38 lb) and was state-of-the-art technology in about 1955. On its right is a solid-state class D amplifier designed in 2008 that can produce about the same amount of

Analog and Mixed-Signal Electronics, First Edition. Karl D. Stephan.

Companion Website: http://wiley.com/go/analogmixedsignalelectronics

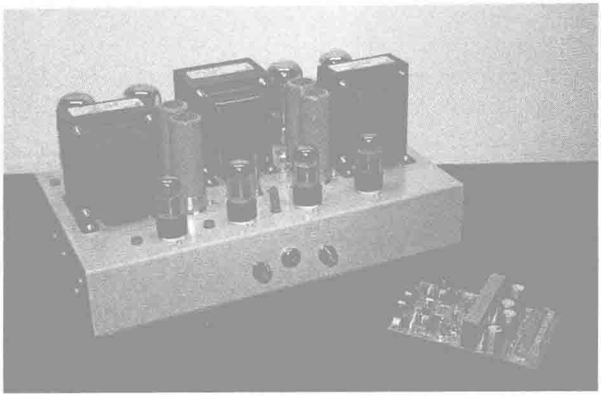

FIGURE 1.1 A comparison: Vacuum-tube audio amplifier (left) using a design circa 1955 and class D amplifier (right) using a design circa 2008.

output power. It is a mixed-signal (analog and digital) design. It measures only 15 cm × 10 cm × 4 cm and weighs only 0.33 kg, not including the power supply, which is of comparable size and weight. The newer amplifier uses its power devices as switches and is much more efficient than the vacuum-tube unit, which is about 50 times its size and weight. So the claim that many analog designs have been made completely obsolete by newer digital and mixed-signal designs is true, as far as it goes.

Sometimes, you will hear defenders of analog technology argue that "the world is essentially analog, and so analog electronics will never go away completely." Again, there's some truth to that, but it depends on your point of view. The physics of quantum mechanics tells us that not only are all material objects made of discrete things called atoms but many forms of energy appear as discrete packets called quanta (photons, in the case of electromagnetic radiation). So you can make just as good an argument for the case that the whole world is essentially digital, not analog, because it can be represented as bits of quanta and atoms that are either there or not there at all.

The fact of the matter is that while the bulk of today's electronics technology is implemented by means of digital circuits and powerful software, a smaller but essential part of what goes into most electronic devices involves analog circuitry. Even if the analog part is as simple as a battery for the power supply, no one has yet developed a battery that behaves digitally: that is, one that provides an absolutely constant voltage until it depletes and drops abruptly to zero. So even designers of an otherwise totally digital system have to deal with the analog problem of power-supply characteristics.

This book is intended for anyone who has an interest in understanding or designing systems involving analog or mixed-signal electronics. That includes undergraduates with a basic sophomore-level understanding of electronics, as well as more advanced undergraduates, graduate students, and professionals in engineering, science, or other fields whose work requires them to learn about or deal with these types of electronic systems. The emphasis is practical rather than theoretical, although enough theory to enable an understanding of the essentials will be presented as needed throughout. Many textbooks present electronics concepts in isolation without any indication of how a component or circuit can be used to meet a practical need, and we will try to avoid that error in this book. Practical applications of the various circuits and systems described will appear as examples, as paper or computer-simulation design exercises, and as lab projects.

1.2 ORGANIZATION OF THE BOOK

The book is divided into three main sections: devices and linear systems (Chapters 2 and 3), linear and nonlinear analog circuits and applications (Chapters 4–7), and special topics of analog and mixed-signal design (Chapters 8–12). A chapter-by-chapter summary follows.

1.2.1 Chapter 2: Basics of Electronic Components and Devices

In this chapter, you will learn enough about the various types of two- and three-terminal electronic devices to use them in simple designs. This includes rectifier, signal, and light-emitting diodes and the various types of three-terminal devices: field-effect transistors (FETs), bipolar junction transistors (BJTs), and power devices. Despite the bewildering number of different devices available from manufacturers, there are usually only a few specifications that you need to know about each type in order to use them safely and efficiently. In this chapter, we present basic circuit models for each type of device and how to incorporate the essential specifications into the model.

1.2.2 Chapter 3: Linear System Analysis

This chapter presents the basics of linear systems: how to characterize a "black box" circuit as an element in a more complex system, how to deal with characteristics such as gain and frequency response, and how to define a system's overall specifications in terms that can be translated into circuit designs. The power of linear analysis is that it can deal with complex systems using fairly simple mathematics. You also learn about some basic principles of noise sources and their effects on electronic systems.

1.2.3 Chapter 4: Nonlinearities in Analog Electronics

While linear analysis covers a great deal of analog-circuit territory, nonlinear effects can both cause problems in designs and provide solutions to other design problems. Noise of various kinds is always present to some degree in any circuit, and in the case of high-gain and high-sensitivity systems dealing with low-level signals, noise can determine the performance limits of the entire system. You will be introduced to the basics of nonlinearities and noise in this chapter and learn ways of dealing with these issues and minimizing problems that may arise from them.